

Chapter 2.

IMPROVEMENTS IN THE COMPUTATIONAL AND ANALYSIS METHODS

The research work described in this chapter is partly based on the following papers :

- R.C. Gupta, *Modifications in the AUTOMESH and other POISSON Group Codes*, Proceedings of the Workshop in Electromagnetic Field Computations, Schnectady, NY (1986).
- R.C. Gupta, *Improvements in the Mesh Generator of the POISSON Group Codes*, Proceedings of the 1987 Particle Accelerator Conference, Washington DC (1987).
- R.C. Gupta, POISSON-BNL, *Computer Codes for Particle Accelerator Design and Analysis: A Compendium*, Los Alamos Accelerator Code Group, Second Edition, LA-UR-90-1766 (1990).

2.1. Introduction

In order to produce the desired high field quality in superconducting magnets, the computational and analysis techniques should be developed to a level which are reliable to an accuracy of $\sim 10^{-4}$. Moreover, the source of differences between the expected and measured harmonics should be understood to assure that it (the source) will not change and that the desired change in harmonics is obtained after an iteration in the design. A method that permits analysis of the actual shape and size of the geometry of various components in the magnet is a useful tool to understand the source of those differences.

The first section of this chapter describes the development of a computer aided cross section measurement and analysis technique which can be used to find the deviation in the coil and iron shape from the ideal design. This method makes use of personal computers (PC) and commercially available hardware and software for them. The second section describes improvements in the computational techniques, in particular the modelling of the cross section with the code POISSON [135]. Since the geometry of superconducting magnets is too complex for the field to be obtained by analytic formulas, numerical methods such as those used in POISSON are essential to obtain the desired results. With the help of the modelling techniques described here, it is possible to define the magnet geometry with improved accuracy.

2.2. Computer Aided Cross-section Measurement and Analysis

The shape of the coil and yoke undergoes significant deformation when a large compressive force is applied on the superconducting coils in the magnet. Typically, the coil and yoke cross section deforms from a circular to an elliptical shape and bends inward on the horizontal plane. Moreover, during the coil curing process, there may be a small change from design in the turn-to-turn spacing (or effective thickness) of the insulated cable. These deformations affect the field quality in the magnet. In order to incorporate these deformations in a magnetic model, the actual mechanical cross section of the coil and iron geometry in the magnet after it is built must be known. Commercially available software such as ANSYS [7] can compute the deformation under the applied force based on a certain model. The results of such calculations [101] depend on the details of the model and are usually not reliable to the desired $25\mu\text{m}$ accuracy. In any case, a confirmation of the mechanical model would be desirable before relying on the accuracy of magnetic field calculations based on the model.

The following method is presently followed [159] to obtain an actual mechanical description of the coil and yoke cross section in the magnet. The magnet is physically cut perpendicular to the axis into a thin slice showing the cross section of the magnet on the two sides of the slice. The slice is referred to as a “*cookie*” and it is etched to enhance the contrast between the insulation, copper and superconductor of the wires. This procedure obviously destroys the magnet. An alternate method [10] was proposed at the SSC laboratory where γ -ray tomography and spectroscopy is used to construct a 3-dimensional image without cutting the magnet. The method, though very appealing and promising, did not in practice reach the required resolution. The schemes which are presently used at BNL still rely on dissecting the magnet. These require a direct mechanical measurement [159] of several thousand wire centers as seen on the cookie or a photograph of it. This task is very demanding in terms of time and human concentration and is subjected to various practical errors. Moreover, it is almost impossible to revisit those measurements since the data processing and other analysis must be done off-line (after the measurements).

The method proposed here is also based on using a cookie to study the magnet cross section. In this method an image of the magnet cross section is digitally stored (rasterized) in a computer where study of the image and data analysis can be efficiently done. The method is based on commercial hardware and software generally used for other purposes. In any case, these are readily available and are relatively inexpensive. The first step in

this method is to scan a photograph of the cookie, or the cookie itself, directly using a commercial scanner such as the HP ScanJet [92]. Such a scanner converts the object into a rasterized image. This rasterized image can be stored to a desired resolution in a variety of popular formats such as TIFF. The above digitization could also be obtained directly using a video camera and special software. The desired accuracy in this step is at the level of 25-50 μm . The issue of overall positional accuracy in the method will be discussed later.

In Fig. 2.2.1, a portion of the cross section of the coil in the 40 mm aperture SSC dipole DSS005 is shown. This was obtained when a photograph of a cookie was scanned. In order to enhance the contrast on the photographic image the cookie was etched and the photographic techniques were optimized for this application. Though in reality one would work on the whole image at a time, here only a part of the 2 layer coil cross section is shown to elaborate the details. One can clearly see the two layers separated by darker insulation. The insulation also separates the various turns (cables) in each layer. The copper appears light gray and it can be seen in the wedge and also at the center of each wire in the inner layer cable. A number of superconducting wires (strands) can be seen in each cable.

This image can now be examined with a number of software packages. A simple software package like *HP Paintbrush* [91] can be used to manually obtain the location of wire centers in Fig. 2.2.1. Alternately, this image can be transported to more advanced programs like AUTOCAD [8] for further analysis. A commercially available program, "*CAD Overlay GS*" [26] converts the TIFF format file to an IGES format file and overlays this image onto AUTOCAD. This conversion maintains the grayscale which is crucial to determining the center of each wire. This software works as an add-on to AUTOCAD, and thus all of the important analytical tools of AUTOCAD software can be utilized. For example, to perform the simple task of obtaining the coordinates of the center of all wires, one would manually mark them with a mouse and at the end of the run, the output file containing the information where the mouse was clicked could be saved. This would create an ASCII file containing the center of the wires. This file can then be post-processed by other programs which, for example, can compute the field harmonics, etc.

The information provided by this method, even at this stage, has already exceeded that which is obtained by other BNL methods. In addition, one can now re-examine the object (image), if desired, and be assured of repeatability since the image can be placed exactly as before. This re-examination could be used, for example, to verify the center position of a particular wire. This repeatability also permits the measurements to be made in several

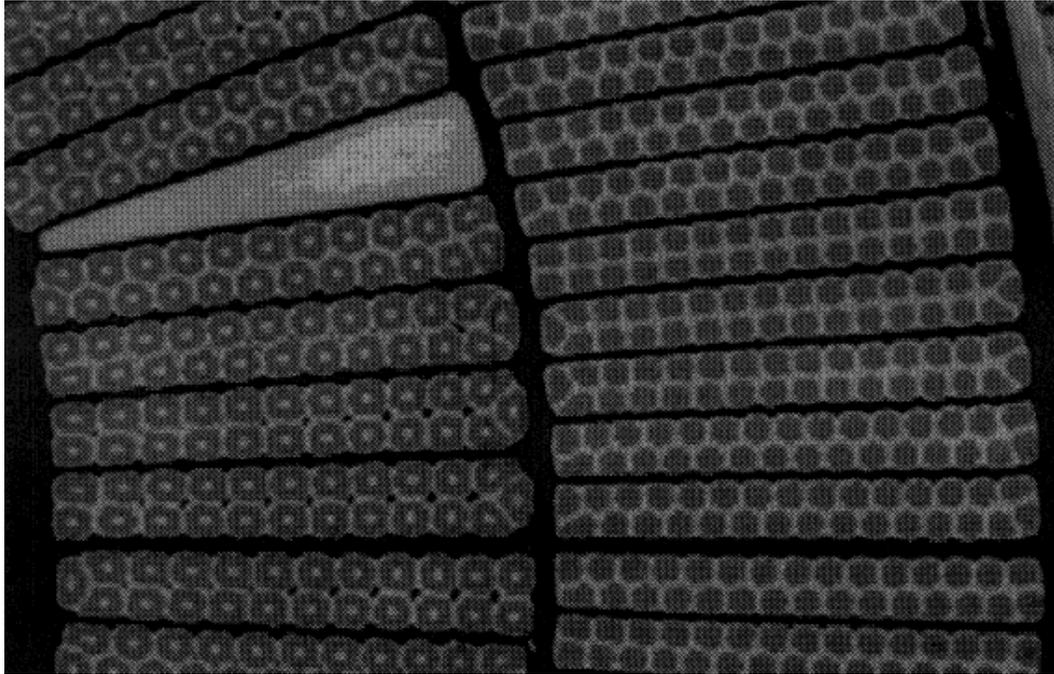


Figure 2.2.1: A raster image of a part of the actual cross-section of the two-layer SSC 40 mm aperture dipole DSS005. After the normal testing, the magnet was physically cut perpendicular to the magnet axis and across the cross section into a small axial length to make what is referred to as a “cookie”. A photograph of the cookie was made after etching. The photograph was scanned and this raster image was electronically saved. The purpose of this exercise is to further study this image with software like “AUTOCAD” [8] to understand the mechanical deformation in the geometry of the coil cross section in the magnet and to compare the measured harmonics with those computed from this geometry (the actual geometry of the magnet as built).

shifts. One can also easily check, for example, whether all the wires were included in the analysis or not, because those wires which were not included would not have a mark which is left by the click of the mouse. These debugging and advanced features were not possible in the earlier methods. One can also zoom the image to any desired magnification to get better accuracy in finding the wire center or to see visually any type of distortion in the magnet geometry.

An important issue in determining the reliability or accuracy of the method is a loss in linearity when the object is translated into a digital image through the photography and scanning process. These non-linear effects, in principle, can be removed by overlaying a high precision grid image which would go through a similar distortion. In the present method the non-linearity is experimentally determined by examining the distortion in the scanned grid scale and then this information can be used to remove the non-linearity in the image. Kahn [101] examined the extent of loss of linearity and observed that the linearity of a high precision scale is maintained within measurement accuracy and other errors.

The next issue which determines the accuracy of the process is that of resolution in the final digitized image. The photographic image itself has a high resolution and therefore the use of a photograph instead of the real object does not incur any loss in resolution. The practical limit in the past was in the image size following the scanning and post-processing. The HP ScanJet scanner used here had a resolution of 1500 DPI (dots per inch). The desired accuracy in the process is $25 \mu m$ (1 mil or $0.001''$) which would require 1000 DPI or more resolution. The memory required for the large photograph when digitized with a high resolution tends to become large. For example, a 10 inch \times 8 inch image would use 1.2 megabytes of storage space if 1500 DPI resolution is used. Kahn [101] used 600 DPI resolution scan to test the accuracy of the method – with each pixel representing 1.67 mil. The typical deviation in the position of any point was 1 or 2 pixel with the maximum being 3 pixel. These errors were found to be of a random nature and therefore should not produce systematic errors (particularly since the statistical sample is large for a few thousand wires) in the results obtained based on these measurements. Moreover this error is consistent with that expected from the error in the scale used and also with the quality of the image used in this calibration. In some applications, however, the errors with 600 DPI resolution may be a factor of two higher than desired. In order to maintain the required accuracy in further analysis, the post processing programs (such as AUTOCAD) should be able to read and accept the images with a resolution matching the images produced in the

scanner. The available resolution (image size in Megabites) was one of the limitations in the study made by Kahn. This should not be a problem now with the advancement in personal computer (PC) technology. Significant advances have been made in recent years not only in the hardware but also in the software, which should result in a significant improvement in the accuracy of the method.

As mentioned earlier, once the image is processed in the AUTOCAD software, one can do a variety of useful online analyses. For example, one can get coil pole angle, size and location of the wedges and individual turns, etc. Moreover, the distortion in the coil or yoke shape can be easily obtained with the help of AUTOCAD. The image can be overlaid on top of the design cross section to compare the measured and mechanical deformations/deviations in the shape, etc. The use of the built-in zooming facilities in the software is helpful in such investigations. These mechanical measurements can be used to verify the mechanical and magnetic modelling and hence to improve the quality of analysis and construction of the magnet.

A cable consists of a large number of wires (23, 30 or 36). In another method the position of a turn (cable) is determined from measurements of the position of all of these individual wires. The proposed AUTOCAD based method provides an option where one can obtain the position of a turn from a single measurement by using a straight line or box fit on the cable surfaces. A turn (insulated cable) can be seen clearly on the screen because of good contrast between the insulation and superconducting wires (see Fig. 2.2.1). In cases where this accuracy is acceptable there is no need to obtain the center position of a large number of wires in the whole magnet. The field harmonic calculations give practically the same results whether one computes the field by integrating over the individual wires in the magnet or over all the cables (each of which contains many wires) in the magnet.

One can also measure the collar, spacer or yoke, etc. by directly putting those objects (or a photograph of them) on the ScanJet. By comparing an image of them before and after the magnet is assembled, one can obtain the deformation at various places which would be useful in checking the results of a mechanical analysis. A partial image of a pair of yoke laminations used in the prototype 80 mm aperture RHIC arc dipoles is shown in Fig. 2.2.2. This raster image was obtained by directly placing the yoke lamination on the scanner. A comparison of the shape of this lamination outside the assembled magnet (as shown here) and inside the assembled magnet (as obtained from the cookie) would give the change in



Figure 2.2.2: A raster image of about one-half of a yoke lamination used in a prototype of the RHIC 80 mm aperture arc dipole. A comparison of the shape of this lamination outside the assembled magnet and inside the assembled magnet gives information about the change in yoke shape due to the large compressive forces used during the magnet assembly.

the shape and the dimensions of the yoke due to the large compressive forces used in the magnet assembly.

This method (the use of digitized images) has been brought to reality with discussion and help from R. Gottschalk, S. Kahn, R. Hogue, K. Power and M. Rehak.

2.3. IMPROVEMENTS IN THE POISSON GROUP CODES

The 2-dimensional POISSON Group computer codes are used to perform electromagnetic field computations for magnets and radio-frequency cavities. They include four separate major programs : AUTOMESH, LATTICE, POISSON and TEKPLOT written in the computer language FORTRAN. The POISSON Group codes were written and developed by Holsinger and Halbach [79,90] and further modified by other authors [27,56,57,63,135]. These programs require a discretization of the geometry with a large number of mesh points (generally over 10,000). The model geometry is defined with the help of nonuniform triangles. The sides of these triangles approximate the curvilinear boundaries of the physical problem. The regions of various material properties and current carrying coils are defined by these boundaries. Program AUTOMESH produces the minimum necessary points on the boundary to complete the description of the bounding surfaces of the regions and assigns them the appropriate properties. The interior mesh points for each region are generated by program LATTICE. Program POISSON finds the solution in terms of the vector potential by the successive point over-relaxation method. Program TEKPLOT is used to graphically display the model, the mesh and the field lines. A more detailed description of these codes can be found in Ref. 135.

The accuracy of the calculations depends on how well the computer model approximates the actual geometry of the problem, especially in the area where the desired accuracy of the solution is high. This is particularly critical when the geometry includes curved boundaries and when the separation between the boundaries of the various regions is relatively small. To deal with such cases one must (a) have a high mesh density in these critical regions and (b) have control on the way the mesh is generated so that the details of the geometry can be incorporated by refining the mesh. An increase in the total number of mesh points (and hence the mesh density everywhere) may be limited not only by the computer resources but would also excessively increase the computational time. To overcome these problems, the POISSON Group codes (in particular AUTOMESH and LATTICE) have been extensively enhanced with over 10,000 lines of additional code. Improved techniques for generating a more optimized mesh have been developed and three new methods of giving AUTOMESH input are described which exploit the use of those techniques. An example will be given for each of these methods that explains these techniques. These improvements enable one to have full control over the way the mesh is generated and in particular the way the mesh density is distributed throughout the model. A higher mesh density in certain

regions coupled with successively lower mesh density in others keeps the accuracy of the field computation high and the requirements on the computer time and computer memory low.

Following is a brief description of the improved AUTOMESH. A detailed description and the improvements in LATTICE and POISSON can be found in Ref. 56 and Ref. 57.

2.3.1. Upgraded AUTOMESH – Input Method No. 1

An input to the new AUTOMESH based on this method is given in Fig. 2.3.1. The model is for a proposed design of a 40 mm aperture 2-in-1 SSC dipole magnet [139]. Though the cross section of the coil is the same in the two apertures, the magnitude of the current may be different. Therefore, a model must be made for one half of the magnet. The model geometry is shown in Fig. 2.3.2. The input conventions and various NAMELIST parameters are compatible with those described in the User's Guide to the POISSON Group codes [135]. Only the use of new NAMELIST parameters will be discussed here. Throughout this section variables starting with X and Y refer to the physical coordinates and K and L to the logical coordinates.

One of the major motivations for improving AUTOMESH was to be able to use a variable mesh size efficiently. This method offers complete control of the mesh size with the help of new NAMELIST parameters (XSTR,XEND), (KSTR,KEND) and/or (YSTR,YEND), (LSTR,LEND). The points at XSTR are assigned the logical coordinate KSTR and at XEND the logical coordinate KEND. The physical increment (DX) between two consecutive logical coordinates is $(XEND-XSTR)/(KEND-KSTR)$. A similar concept is adopted for (YSTR,YEND) and (LSTR,LEND). The scale, once so determined, is used in subsequent regions until changed. Any such scale can be stored by the NAMELIST parameter ICARY=1 and may be recalled by specifying ICARY=-1. ICARY=0 (Default) uses the current scale. In addition to providing complete control of the mesh size in each region, the method also permits a change in mesh size within the same region. This is accomplished by breaking a region into a number of contiguous sub-regions. The NAMELIST parameter ICONT=1 indicates that the next region is a continuation of the present region. Once a region is broken into several sub-regions, one can use the techniques described above to use

different scales. `ICONT=0` signals the end of the continuation. The `NAMELIST` parameter `NEXT` is used (in the first region) to store information about the number of such extra regions.

In the example of Fig. 2.3.1 and Fig. 2.3.2, a very dense mesh is used in the coil regions. The maximum accuracy in the field calculations is desired at the center of the coil. The mesh size is reduced gradually in the regions away from the coils where the magnetic field is also lower and therefore an error in the geometry has only a small effect. This strategy of change in mesh size keeps the number of mesh points low and, therefore, the computation time low without significantly compromising the accuracy of the results. The coils in the example have two layers - inner and outer. The mesh size in the coil region is sufficient to separate different regions (blocks) of coils within the inner and outer layers. It is, however, not enough to produce a separation between the two layers and to devise a small midplane gap. To incorporate these details the coils are moved away by one unit in the logical coordinates – in physical space the coils do not move [56].

A more detail description of this model and method can be found in [56].

```

2-in-1 Magnet for SSC.
$REG NREG=27,IREG=1,MAT=1,NPOINT=3,NEXT=2
XMIN=-30.,YMIN=0.,XMAX=30.,YMAX=30.
LMAX=68,KMAX=165,ICONT=1
XSTR=30.,XEND=30.,KSTR=1,KEND=165
YSTR=15.0,YEND=30.,LSTR=43,LEND=685
SPO R=30.,THETA=30.0,$
SPO X=0.,Y=30.,NT=25
SPO R=30.,THETA=150.,NT=25
$REG YSTR=0.,YEND=15.0,LSTR=1,LEND=43,
NPOINT=5,ICONT=05
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SPO X=30.,Y=0.,NT=25
SPO X=0.,Y=0.,NT=15
SPO X=30.,Y=0.0,$
SPO R=30.,THETA=30.,NT=25
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XSTR=-17.79,XEND=17.79,KSTR=9,KEND=157
YSTR=8.895,YEND=17.79,LSTR=41,LEND=605
SPO R=17.79,THETA=30.0,$
SPO X=2.54,Y=17.608,NT=25
SPO X=2.54,Y=16.985,NT=15
SPO X=-.795,Y=16.985,IK=86,IL=585
SPO X=-.795,Y=16.2135
SPO X=1.3494,Y=16.2135
SPO X=1.3494,Y=15.245
SPO X=-.795,Y=15.245
SPO X=-.795,Y=14.6055
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SPO X=-.795,Y=15.245
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SPO X=-.795,Y=16.2135
SPO X=-.795,Y=16.2135
SPO X=-.795,Y=16.9855
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SPO X=-2.54,Y=17.6085
SPO R=17.79,THETA=150.,NT=25
$REG YSTR=0.,YEND=8.895,LSTR=1,LEND=41
ICONT=0,NPOINT=45
SPO R=17.79,THETA=150.0,$
SPO X=17.79,Y=0.,NT=25
SPO X=17.79,Y=0.0,$
SPO R=17.79,THETA=30.,NT=25
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YSTR=1.15,YEND=6.236,LSTR=8,LEND=355
SPO X=2.5603,Y=0.,X0=0.,Y0=3.6754$
SPO X=0.,Y=2.5603,X0=0.,Y0=3.6754,NT=25
SPO X=-2.5603,Y=0.,X0=0.,Y0=3.6754,NT=25
SPO X=0.,Y=-2.5603,X0=0.,Y0=3.6754,NT=25
SPO X=2.5603,Y=0.,NT=2,X0=0.,Y0=3.6754$
$REG XSTR=2.6987,XEND=13.8113,KSTR=89,KEND=149
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SPO X=5.5563,Y=0.,X0=8.255,Y0=0.0,$
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$REG MAT=1,IREG=5,NPOINT=13,
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$REG IREG=6,NPOINT=6,MAT=1
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SPO R=3.993,THETA=109,NT=2,X0=8.255,Y0=0.0,$
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$REG MAT=1,IREG=23,MAT=1,NPOINT=5,CUR=16800.$
SPO R=1.999,THETA=64.962,X0=8.255,Y0=0.0,$
SPO R=2.962,THETA=77.615,X0=8.255,Y0=0.,NT=25$
SPO R=2.962,THETA=76.349,X0=8.255,Y0=0.,NT=1$
SPO R=2.962,THETA=66.226,X0=8.255,Y0=0.,NT=25$
SPO R=1.999,THETA=64.962,X0=8.255,Y0=0.,NT=1$
$REG MAT=1,IREG=26,NPOINT=6,CUR=33600.,
XSTR=-12.248,XEND=4.262,KSTR=23,KEND=735
SPO R=1.999,THETA=179.782,X0=8.255,Y0=0.0,$
SPO R=1.999,THETA=154.483,X0=8.255,Y0=0.,NT=25$
SPO R=2.962,THETA=159.6295,X0=8.255,Y0=0.,NT=1$
SPO R=2.962,THETA=161.211,X0=8.255,Y0=0.,NT=25$
SPO R=2.962,THETA=179.853,X0=8.255,Y0=0.,NT=25$
SPO R=1.999,THETA=179.782,X0=8.255,Y0=0.,NT=1$
$REG IREG=27,MAT=1,NPOINT=6,CUR=39200.$
SPO R=1.999,THETA=152.733,X0=8.255,Y0=0.0,$
SPO R=1.999,THETA=123.23,X0=8.255,Y0=0.,NT=25$
SPO R=2.962,THETA=126.164,X0=8.255,Y0=0.,NT=1$
SPO R=2.962,THETA=131.802,X0=8.255,Y0=0.,NT=25$
SPO R=2.962,THETA=149.799,X0=8.255,Y0=0.,NT=25$
SPO R=1.999,THETA=152.733,X0=8.255,Y0=0.,NT=1$
$REG MAT=1,IREG=28,MAT=1,NPOINT=5,CUR=16800.$
SPO R=1.999,THETA=115.038,X0=8.255,Y0=0.0,$
SPO R=1.999,THETA=102.385,X0=8.255,Y0=0.,NT=25$
SPO R=2.962,THETA=103.651,X0=8.255,Y0=0.,NT=1$
SPO R=2.962,THETA=113.774,X0=8.255,Y0=0.,NT=25$
SPO R=1.999,THETA=115.038,X0=8.255,Y0=0.,NT=1$

```

Figure 2.3.1: An input to AUTOMESH of the POISSON Group codes for creating a mesh based on the upgraded AUTOMESH – Input Method No. 1. The model is for a proposed design of a 40 mm aperture 2-in-1 SSC dipole magnet.

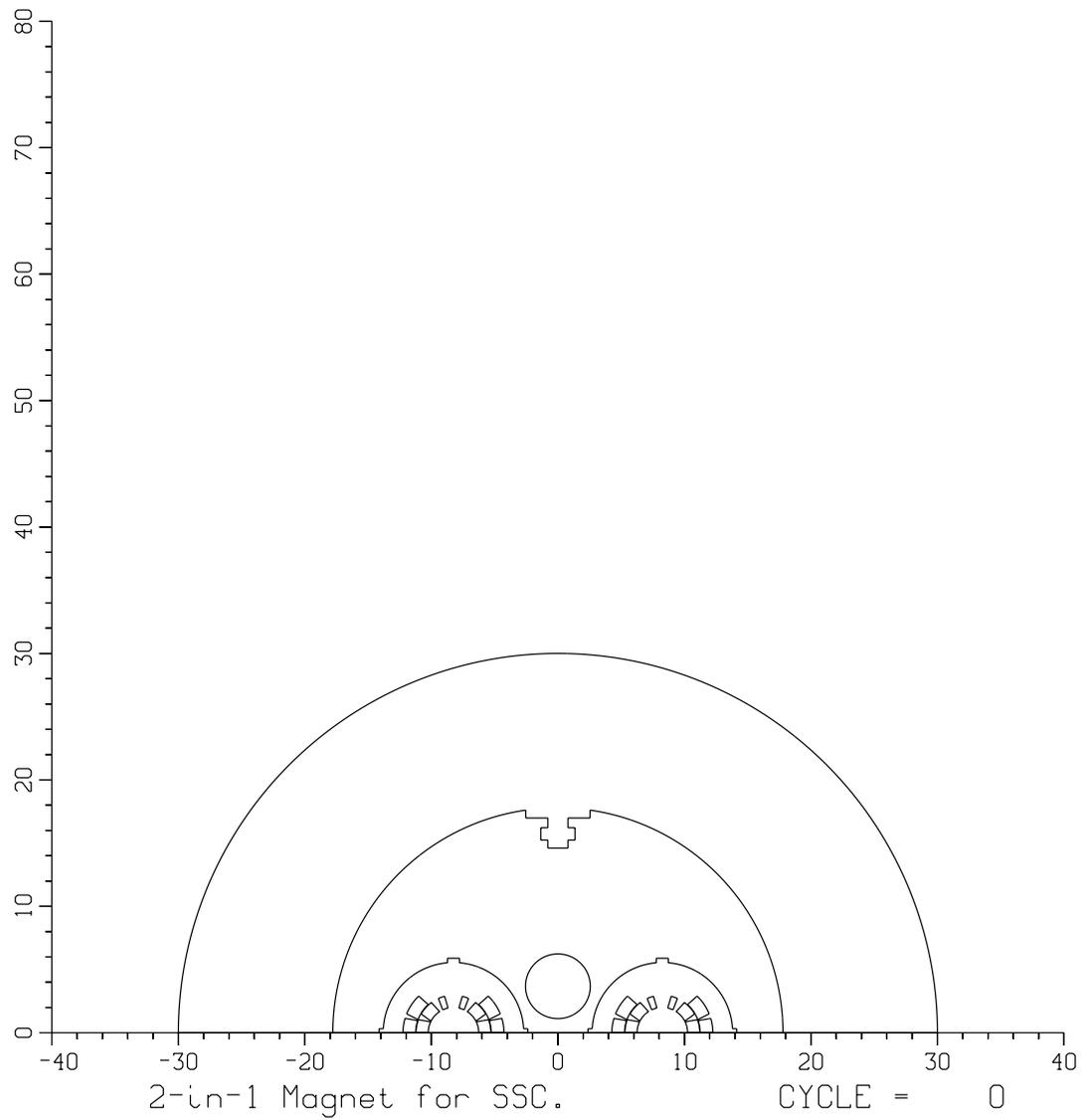


Figure 2.3.2: A POISSON model for the example based on the AUTOMESH Input Method No. 1. The model is for a proposed design of a 40 mm aperture 2-in-1 SSC dipole magnet.

2.3.2. Upgraded AUTOMESH – Input Method No. 2

In this method, the distribution of the mesh density is managed with the help of several special regions, referred to here as SREG (normal regions are referred to as REG). The purpose of these special regions is to generate a preliminary but complete mesh with appropriate calls to LATTICE before the actual run of AUTOMESH starts. The input to AUTOMESH contains NSREG special regions in addition to the NREG normal regions, as shown in the example given in Fig. 2.3.3. The special regions must be given before the normal regions and most of the rules and conventions which apply to normal regions apply to these special regions as well. However, there are the following three exceptions :

- Instead of using the NAMELIST variables MAT, CUR etc., one would use new NAMELIST variables for defining the mesh size and other related quantities. The use of these variables SX0,SX,NX0,NX, SY0,SY,NY0,NY (having zero default values) is explained below by an example :

```
$ SREG SX=10.,NX=10,SY0=2.,SY=5.,NY0=8,NY=6 $
```

This will make 10 (NX) divisions between 0.0 (SX0) and 10.0 (SX) in the X dimension and 6 (NY) divisions between 2.0 (SY0) and 5.0 (SY) in the Y dimension; moreover 8 (NY0) mesh points will be left before 2.0 (SY).

- The first special region will be automatically generated as a rectangular region with the following points in the specification of the first region :

$$(SX0,SY0), (SX,SY0), (SX,SY), (SX0,SY), (SX0,SY0).$$

In the example given in Fig. 2.3.3, these points are : (0.,0.), (0.,25.), (25.,25.), (25.,0.) and (0.,0.). The next NSREG regions must be explicitly given but they need not, however, have a rectangular shape.

- These special regions should either be closed regions or their end points should lie on a region boundary of a previously defined special region.

The implementation of the mesh density management system into the program is described here. In each special region the program freshly computes parameters such as XMIN, XMAX, DX, . . . with the help of NAMELIST variables SX0, SX, NX0, NX, . . . The necessary points on the boundary of each special region are found and the region data are generated. An intermediate file TAPE74.DAT;1 (similar to TAPE73.DAT) is created with

the NSREG+1 number of special regions. At this stage the program calls several subroutines of LATTICE to generate a complete mesh using the file TAPE74.DAT;1 as input. This mesh is later used to find the logical coordinates in the normal regions.

In addition to the above modifications, the four new variables XADD, YADD, RADD, TADD in the \$REG NAMELIST statement are also included. These variable are used to bias (shift) the path of finding the logical coordinates in a certain preferred direction. They are essential in resolving two curves when the separation between them is less than a mesh spacing.

An example which demonstrates the complete use of this method is given in Fig. 2.3.3 which is the input to AUTOMESH. The model geometry of this problem is shown in Fig. 2.3.4. The mesh generated by the above input of AUTOMESH is shown in Fig. 2.3.5. The model described here is for a coldmass of the 40 mm aperture SSC dipole magnet [139]. Because of the dipole symmetry, only a quadrant of the dipole magnet need be included in the model.

To resolve a small separation between the inner and the outer layers, a negative value (-0.06) of RADD for the coil regions in the inner layer (IREG=11, IREG=12, IREG=13) and a positive value (+0.06) for the regions in the outer layer (IREG=14 and IREG=15) is used. It logically increases the separation between the two layers by 0.12 cm. Similarly, to resolve an angular separation between the first and second blocks in both inner and outer layers, an angular bias is used with the variable TADD in the second blocks (region number 12 and 15). A very small midplane gap is incorporated with the help of parameter YADD in the first blocks of these two layers (see IREG = 11 and IREG = 14).

The accuracy of the field computations at the center of the aperture depends on a good coil description. Therefore, as shown in Fig. 2.3.5, a very dense mesh is used in the coil region. To keep the total number of mesh points low the mesh density is successively reduced in the outer regions.

A more detail description of this model and method can be found in Ref. 57.

```

A Superconducting Dipole Magnet
$REG NSREG=3,NREG=11,SX=25.,NX=70,SY=25.,NY=70$
$SREG SX=14.0,NX=62,SY=14.0,NY=62,NPOINT=2$
$SPO X=14.0,Y=0.$
$SPO X=0.,Y=14.0,NT=2$
$SREG SX=6.0,NX=40,SY=6.0,NY=40,NPOINT=2$
$SPO X=6.0,Y=0.$
$SPO X=0.,Y=6.0,NT=2$
$SREG SX=4.20,NX=30,SY=3.25,NY=30,NPOINT=3$
$SPO X=4.2,Y=0.$
$SPO R=4.2,THETA=51.,NT=2$
$SPO X=0.,Y=3.25$
$REG IREG=1,MAT=1,CUR=0.,NPOINT=4$
$PO X=25.,Y=0.$
$PO X=0.,Y=25.,NT=2$
$PO X=0.,Y=0.$
$PO X=25.,Y=0.$
$REG IREG=2,MAT=3,CUR=0.,NPOINT=8$
$PO X=12.9791,Y=0.$
$PO X=12.9791,Y=1.905$
$PO X=13.1995,Y=1.905$
$PO X=2.159,Y=13.1604,NT=2$
$PO X=2.159,Y=10.6172$
$PO X=0.,Y=10.6172$
$PO X=0.,Y=0.$
$PO X=12.9791,Y=0.$
$REG MAT=1,IREG=3,NPOINT=4$
$PO R=1.4605,THETA=0.,X0=5.08,Y0=9.525$
$PO R=1.4605,THETA=120.,NT=2,X0=5.08,Y0=9.525$
$PO R=1.4605,THETA=240.,NT=2,X0=5.08,Y0=9.525$
$PO R=1.4605,THETA=0.,NT=2,X0=5.08,Y0=9.525$
$REG MAT=1,IREG=4,NPOINT=4$
$PO R=0.4832,THETA=0.,X0=10.16,Y0=6.915$
$PO R=0.4832,THETA=120.,NT=2,X0=10.16,Y0=6.915$
$PO R=0.4832,THETA=240.,NT=2,X0=10.16,Y0=6.915$
$PO R=0.4832,THETA=0.,NT=2,X0=10.16,Y0=6.915$
$REG IREG=5,MAT=1,NPOINT=8$
$PO X=5.8865,Y=0.$
$PO X=5.8865,Y=.3207$
$PO X=5.5470,Y=.3207$
$PO X=0.254,Y=5.5505,NT=2$
$PO X=0.254,Y=5.823,NT=1$
$PO X=0.,Y=5.823 $
$PO X=0.,Y=0. $
$PO X=5.8865,Y=0.$
$REG NPOINT=3,IREG=6$
$PO X=4.2,Y=0.$
$PO R=4.2,THETA=51.,NT=2$
$PO X=0.,Y=3.25$
$REG MAT=1,IREG=11,NPOINT=5,
CUR=35400.,RADD=-0.06,YADD=0.08$
$PO R=1.999,THETA=0.218$
$PO R=1.999,THETA=25.517,NT=2$
$PO R=2.962,THETA=20.463,NT=1$
$PO R=2.962,THETA=0.15,NT=2$
$PO R=1.999,THETA=0.218$
$REG IREG=12,MAT=1,NPOINT=5,
CUR=41300.,RADD=-0.06,TADD=2.5$
$PO R=1.999,THETA=27.267$
$PO R=1.999,THETA=56.77,NT=2$
$PO R=2.962,THETA=53.836,NT=1$
$PO R=2.962,THETA=30.201,NT=2$
$PO R=1.999,THETA=27.267$
$REG MAT=1,IREG=13,MAT=1,NPOINT=5,
CUR=17700.,RADD=-0.06$
$PO R=1.999,THETA=64.962$
$PO R=1.999,THETA=77.615,NT=2$
$PO R=2.962,THETA=76.349,NT=1$
$PO R=2.962,THETA=66.226,NT=2$
$PO R=1.999,THETA=64.962$
$REG MAT=1,IREG=14,NPOINT=5,
CUR=47200.,RADD=0.06,YADD=0.08$
$PO R=2.987,THETA=0.15$
$PO R=2.987,THETA=18.789,NT=2$
$PO R=3.993,THETA=16.484,NT=1$
$PO R=3.993,THETA=0.11,NT=2$
$PO R=2.987,THETA=0.15,NT=1$
$REG MAT=1,IREG=15,NPOINT=5,
CUR=70800.,RADD=0.06,TADD=2.0$
$PO R=2.987,THETA=20.278$
$PO R=2.987,THETA=48.198,NT=2$
$PO R=3.993,THETA=46.5,NT=1$
$PO R=3.993,THETA=21.975,NT=2$
$PO R=2.987,THETA=20.278,NT=1$

```

Figure 2.3.3: An input to AUTOMESH of the POISSON Group codes for creating a mesh based on the upgraded AUTOMESH – Input Method No. 2. The model described here is for the coldmass of the 40 mm aperture SSC dipole magnet.

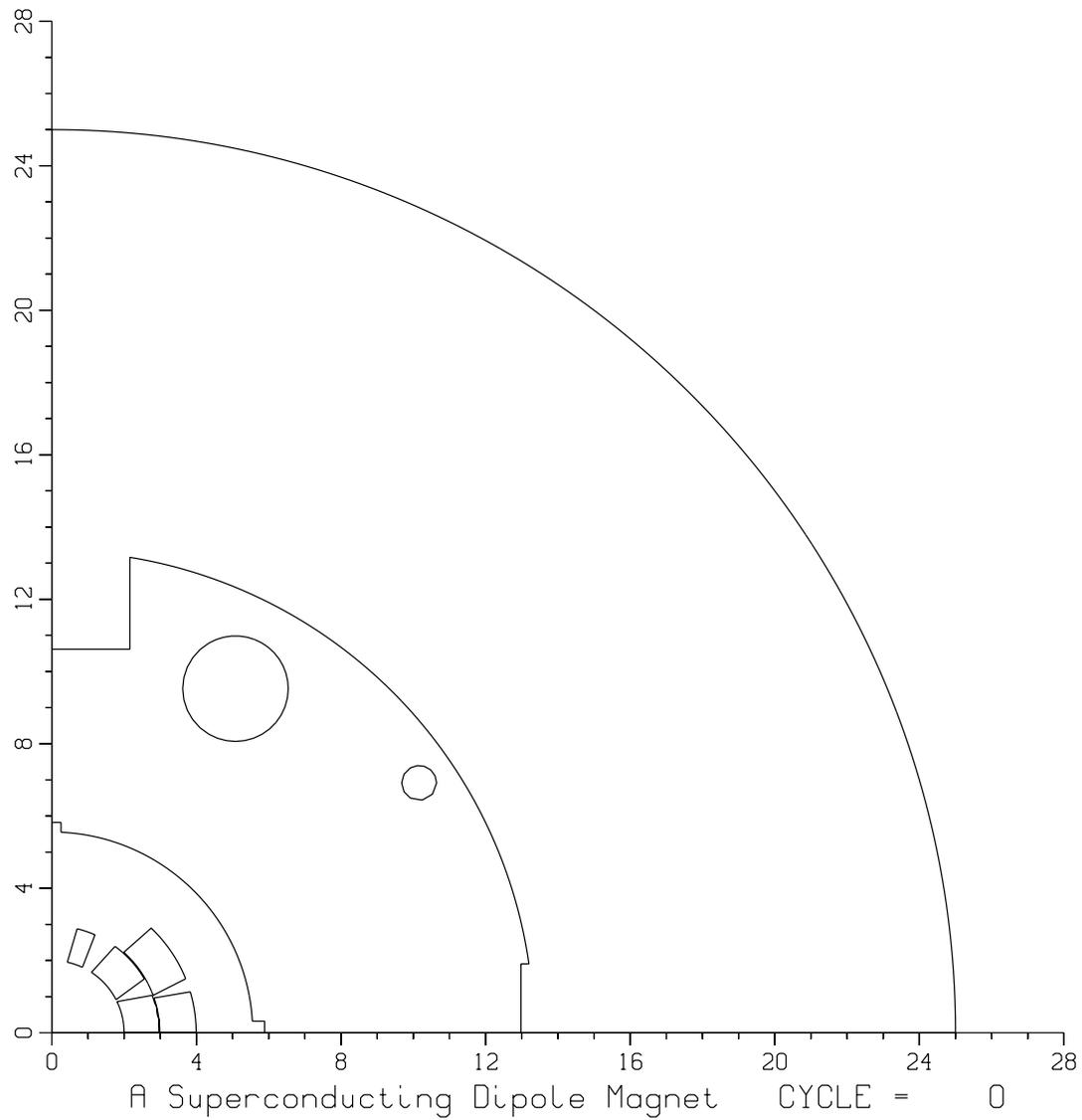


Figure 2.3.4: The POISSON model for the example given, using the AUTOMESH Input Method No. 2. The model is for a 40 mm aperture SSC dipole magnet.

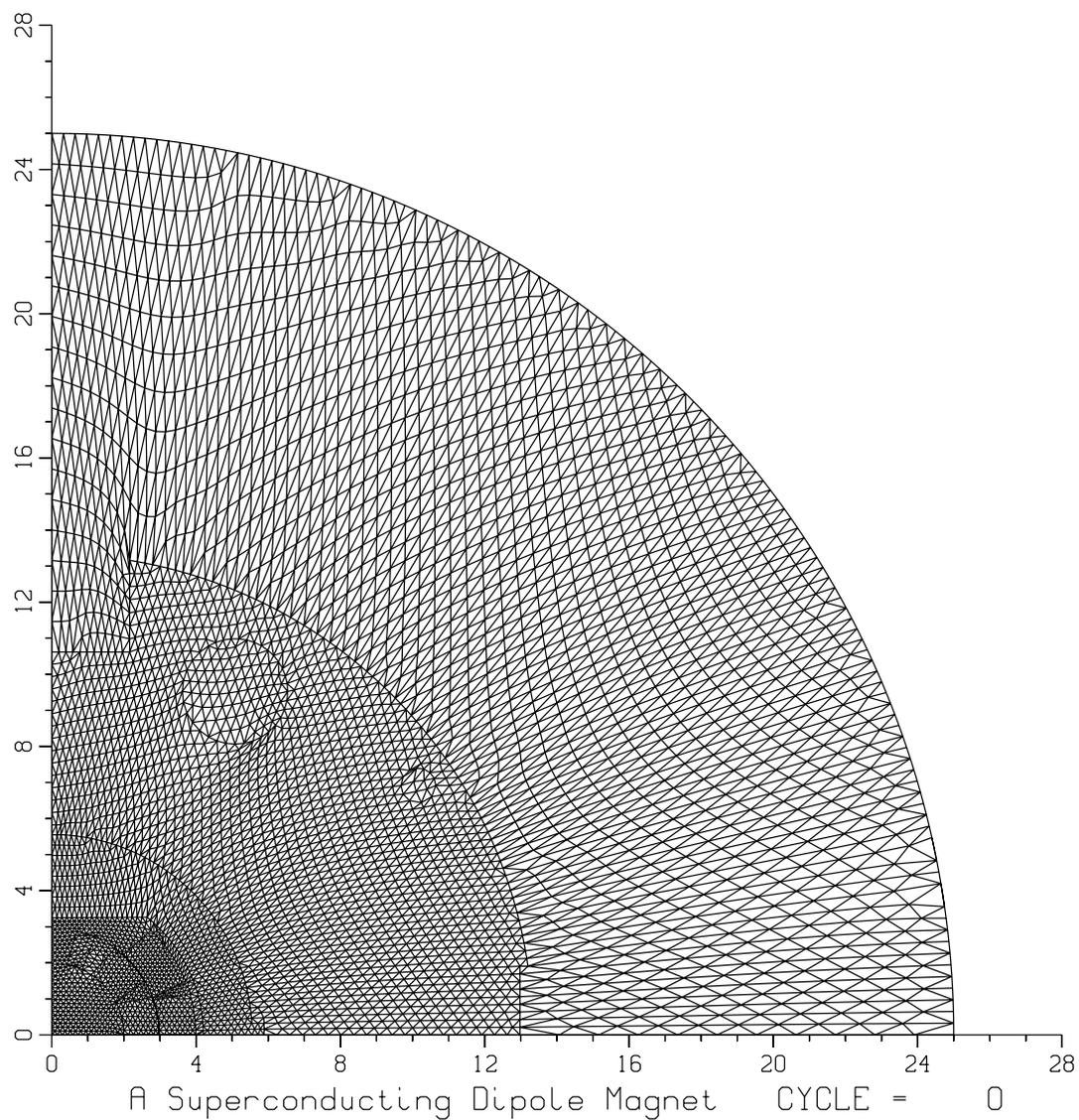


Figure 2.3.5: The mesh for a POISSON model generated by the AUTOMESH Input Method No. 2. The model is for a 40 mm aperture SSC dipole magnet. A higher mesh density is used in the aperture region and a gradually decreasing mesh density in the regions away from it. This combination increases the accuracy of the field calculations in the magnet aperture without proportionally increasing the number of mesh points.

2.3.3. Upgraded AUTOMESH – Input Method No. 3

From a user point of view, conceptually this method is an extension and generalization of the original XREG method for varying the mesh size in the problem. However, in the original method, one was allowed to have only three different mesh sizes with the restriction that the ratio of the different mesh sizes should exactly be 2:1. In the method described here, one can have up to 18 different mesh sizes with no restrictions. This is true in both the horizontal and vertical planes and as described below one can use both Cartesian and polar coordinates to define the variable mesh size.

The mesh size is defined by new namelist variables (XCARN, KCARN) and (YCARn, LCARn) in Cartesian coordinates and by (RPOLn, KPOLn) and (TPOLn, LPOLn) in polar coordinates (here “n” is a number whose value can be between 1 and 9). There can be an offset in the scale in the case of polar coordinates. This offset is defined by the variables XOPn and YOPn. These polar coordinates are converted into Cartesian ones by simple trigonometric relations.

This method is explained here with the example of input shown in Fig. 2.3.6. The input is for a CBA 2-in-1 magnet [20] and the model based on this input is shown in Fig. 2.3.7 First the working of XCARN and KCARN is discussed. This example illustrates the use of XCARN and KCARN with $XCAR1=-23.139$, $XCAR2=-21.412$, $XCAR3=-2.7686$, ... and $KCAR1=15$, $KCAR2=20$, $KCAR3=83$... This means that K is 15 for X=-23.139, and K is 20 for X=-21.142. If this portion (X=-23.139 to X=-21.412) is not further divided, then the computed DX (the average spacing between mesh points on the horizontal plane) between XCAR1 and XCAR2 will be $(-21.412+23.139)/(20-15)=0.3454$. Similarly between XCAR2 and XCAR3 the DX will be $(-2.7686+21.412)/(83-20)=0.2959$. A similar concept is used for producing the desired mesh size DY with the variables YCARn and LCARn.

The polar coordinate specification is given with the help of RPOLn and TPOLn. For $RPOL5=8.678$, $TPOL5=180.$, $XOP5=12.065$, $KPOL5=108$ and $LPOL5=1$, the computed X will be $RPOL5*\text{COS}(TPOL5) + X0 = 3.387$, and K will be $KPOL5 = 108$. Similarly, the computed Y will be $RPOL5*\text{SIN}(TPOL5) + Y0=0.$, and L will be $LPOL5=1$.

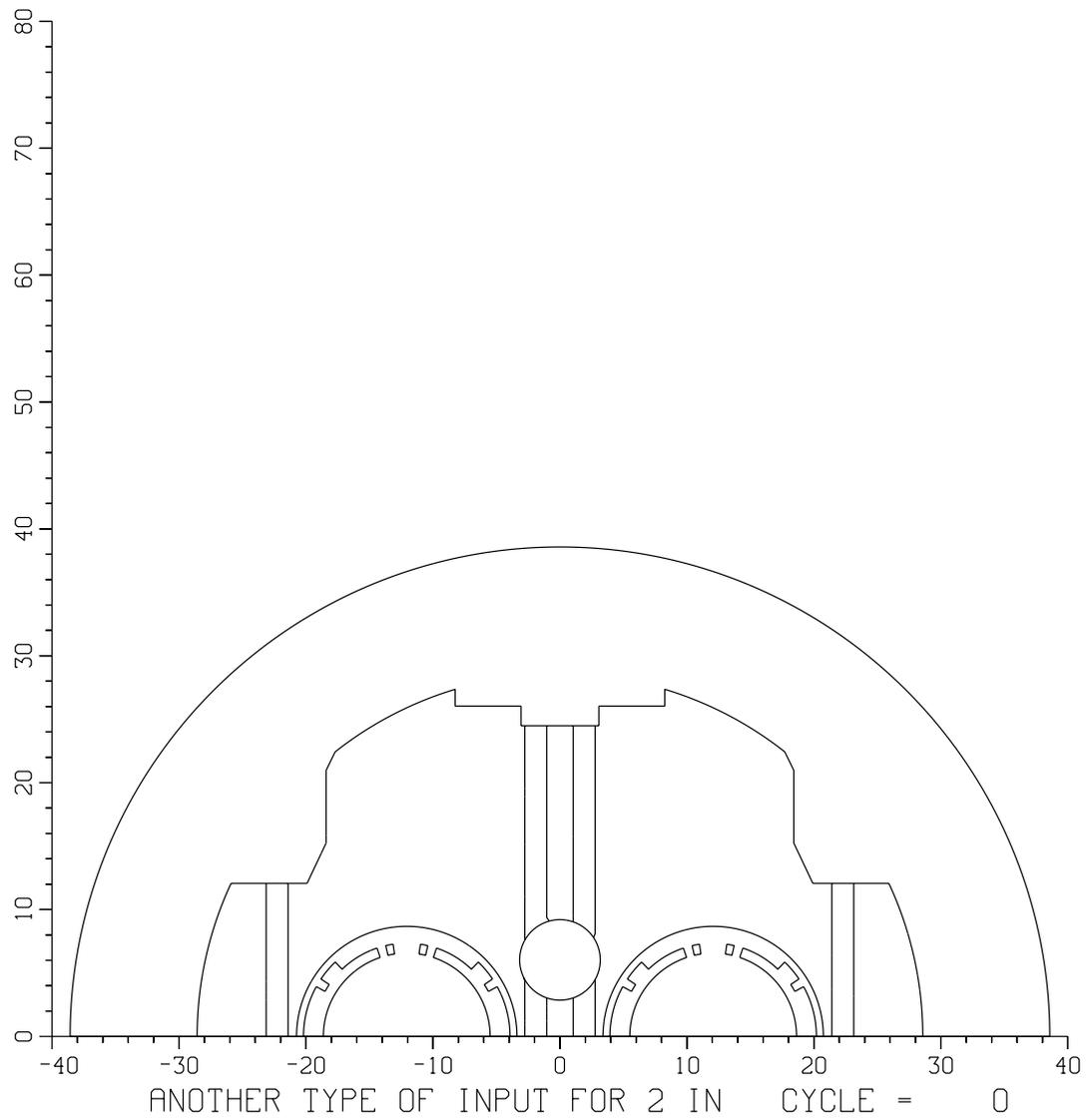


Figure 2.3.7: A POISSON model for the example based on the AUTOMESH Input Method No. 3. The model is for a 130 mm aperture 2-in-1 CBA dipole magnet.

2.4. Conclusions on the Improvements in the Computational and Analysis Methods

A computer aided cross section measurement and analysis method has been developed to evaluate the mechanical deformation on the coil and yoke cross section under large compressive forces. The method creates a digital image of the cross section which can be compared with the original design or with expected mechanical deformations. This method was not used during the R&D phase of the RHIC magnet program in a significant way because at that time the resolution of the image in the support software was marginal and other methods were in use. However, the advances in computer technology over the last several years makes this method quite attractive now. The major advantage of this method is the availability of a digitized image on the computer. Powerful commercial software like AutoCAD can work with that image to do a variety of analyses.

The POISSON Group codes have been extensively improved to enhance their capability for making computer models. The use of these improved techniques allows an efficient use of the mesh points to define the problem. A high mesh density in the critical regions coupled with successively lower mesh density further away keeps the accuracy of the field calculations high and the computation time low. The POISSON Group codes have been used throughout this research work to perform most of the field calculations, especially in analyzing the contribution to the magnetic field from the iron yoke.